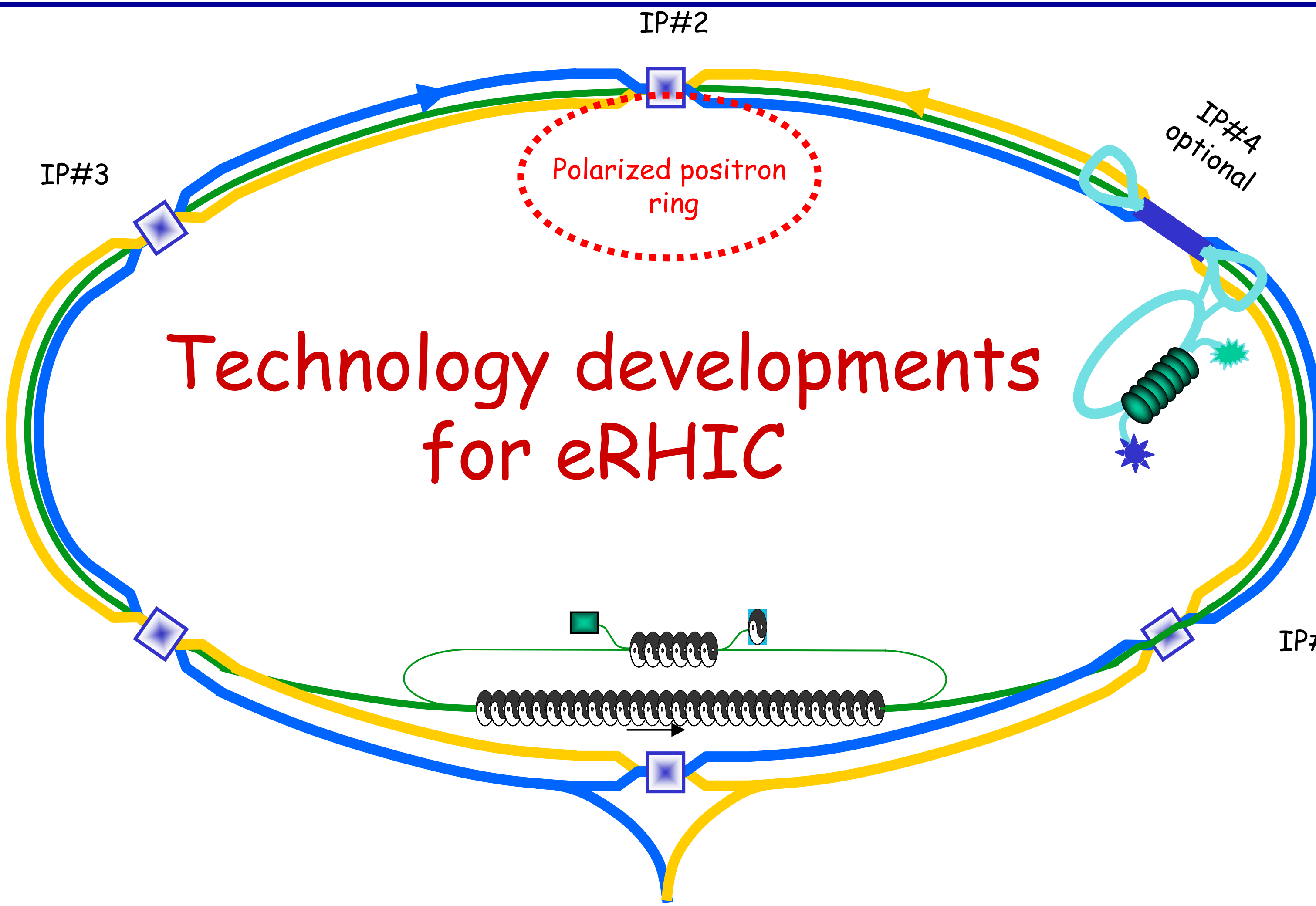

Technology developments for eRHIC

Vladimir N. Litvinenko for eRHIC team

Collider Accelerator Department, Brookhaven National Laboratory, Upton, NY, USA

Credits

….L.Ahrens, D.Anderson, M.Bai, D.P.Barber,J.Beebe-Wang, I.Ben-Zvi, M.Blaskiewicz, J.M.Brennan, R.Calaga, X.Chang, E.D.Courant, A.Deshpande, M.Farkhondeh, A.Fedotov, W.Fischer, W.Franklin, W.Graves, H.Hahn, D.Kayran, J.Kewisch, V.N.Litvinenko, W.W.MacKay, R.Milner, C.Montag, A.V.Otboev, S.Ozaki, B.Parker, S.Peggs, E. Pozdeyev, V.Ptitsyn, T.Roser, A.Ruggiero, Yu.M.Shatunov, B.Surrow, S.Tepikian, C.Tschalaer, D.Trbojevic,J. van der Laan, D.Wang, F.Wang, V.Yakimenko, S.Y.Zhang, A.Zolfaghari, T.Zwart…..

BNL , Upton, NY, USA
MIT-Bates, Middleton, MA, USA
TJNAF, Newport News, VA, USA
SUNY, Stony Brook, NY, USA
BINP, Novosibirsk, Russia
DESY, Hamburg, Germany

Work done in collaboration with many leading institutions:

- National Laboratories
  - Fermilab, JLab, MIT/Bates
- Universities
  - Stony Brook, Indiana
- International Labs
  - BINP, GSI, DESY

Main developments

- Electron and stochastic cooling for ions and protons
  - R&D ERL and SRF
- Increase of polarized proton beam intensity to 111 bunches x 1.4 10^{11} protons
- Better understanding of beam stability in linac-ring eRHIC
  - disruption is not a problem
  - BNL's SRF linac give TBBU threshold ~ 3 A (0.45 needed)
- Improvement in QE for GaAs cathodes in polarized guns
- Small-gap magnets for ERL loops for eRHIC
  - leads to comparable prices for ring-ring and linac-ring

Goals for eRHIC

Physics Requirements

- To provide electron-proton and electron-ion collisions
- Energy ranges:
  - 2-10 GeV polarized e^- or 10 GeV polarized e^+
  - 26-250 GeV polarized protons or 100 GeV/u Au
- Luminosities:
  - > 10^{33} $cm^{-2}s^{-1}$ region for e-p
  - > 10^{31} $cm^{-2}s^{-1}$ region for e-Au
- >70% polarization degree for both lepton and proton beams
- Longitudinal polarization in the collision point

eRHIC

Zeroth-Order Design Report

BNL: L. Ahrens, D. Anderson, M. Bai, J. Beebe-Wang, I. Ben-Zvi, M. Blaskiewicz, J.M. Brennan, R. Calaga, X. Chang, E.D. Courant, A. Deshpande, A. Fedotov, W. Fischer, H. Hahn, J. Kewisch, V. Litvinenko, W.W. MacKay, C. Montag, S. Ozaki, B. Parker, S. Peggs, T. Roser, A. Ruggiero, B. Surrow, S. Tepikian, D. Trbojevic, V. Yakimenko, S.Y. Zhang
MIT-Bates: W. Franklin, W. Graves, R. Milner, C. Tschalaer, J. van der Laan, D. Wang, F. Wang, A. Zolfaghari and T. Zwart
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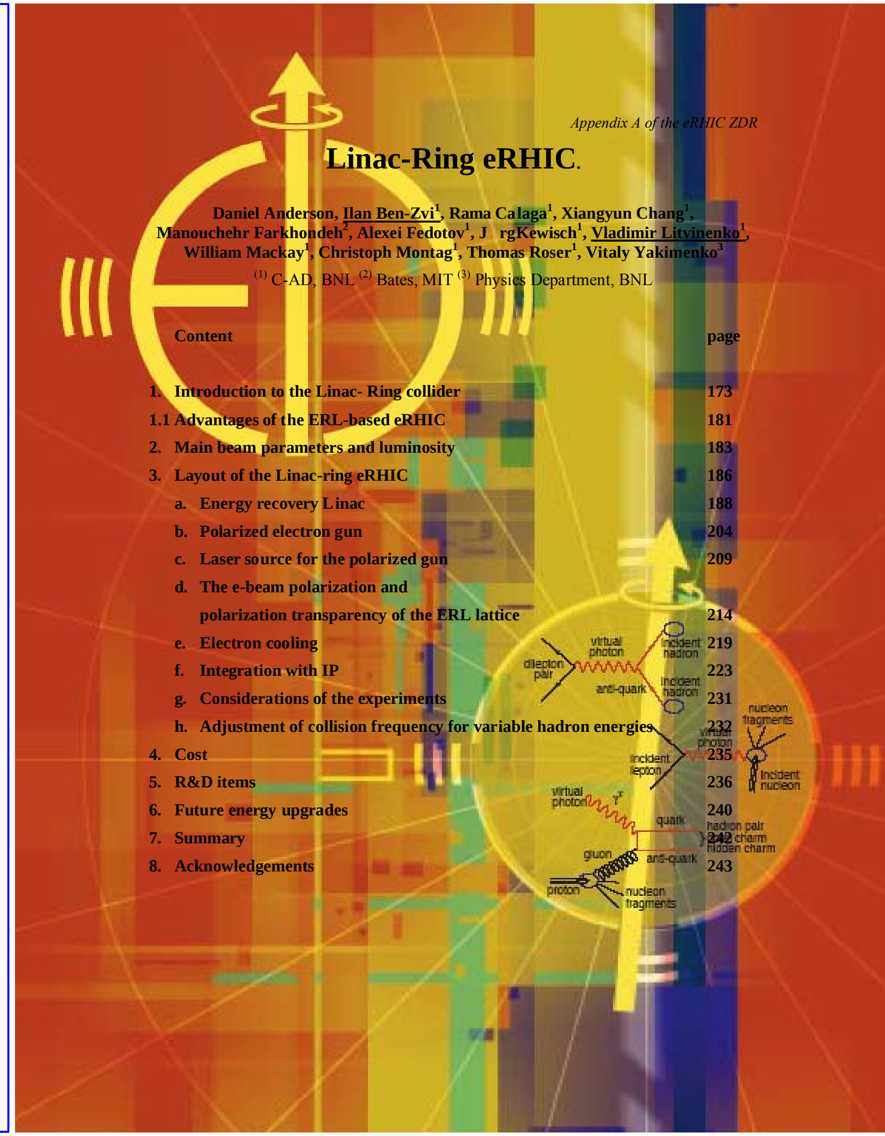
DESY: D.P. Barber

Editors: M. Farkhondeh (MIT-Bates) and V. Ptitsyn (BNL)

http://www.agsrhichome.bnl.gov/eRHIC/



Appendix A of the eRHIC ZDR

Linac-Ring eRHIC.

Daniel Anderson, Ilan Ben-Zvi[1], Rama Calaga[1], Xiangyun Chang[1], Manouchehr Farkhondeh[2], Alexei Fedotov[1], J rgKewisch[1], Vladimir Litvinenko[1], William Mackay[1], Christoph Montag[1], Thomas Roser[1], Vitaly Yakimenko[3]
(1) C-AD, BNL (2) Bates, MIT (3) Physics Department, BNL

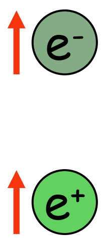
Content **page**

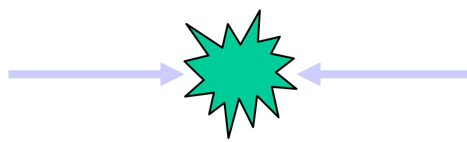
eRHIC Scope -QCD Factory

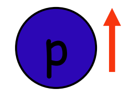
Electron accelerator

RHIC

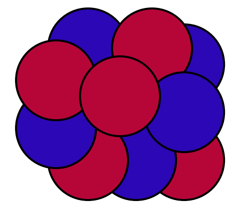
Polarized leptons
$_{2}\downarrow$5-10$\uparrow^{20}$ GeV



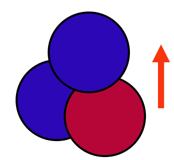




Polarized protons
$_{25}\downarrow$ 50-250 GeV



Heavy ions (Au)
50-100 GeV/u



Polarized light ions
(He^3) 167 GeV/u

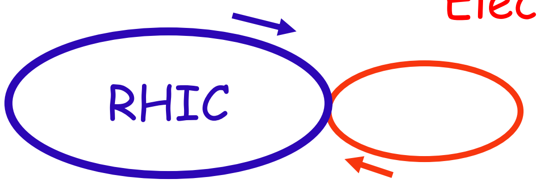
70% beam polarization goal

Center mass energy range: 15➢-100✓ GeV

How eRHIC can be realized?

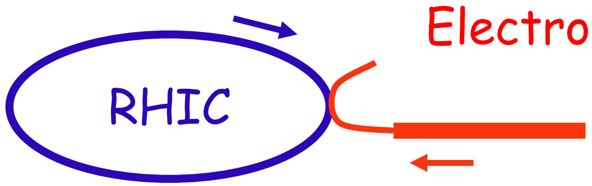
- Two main design options:
  - Ring-ring:

Electron storage ring

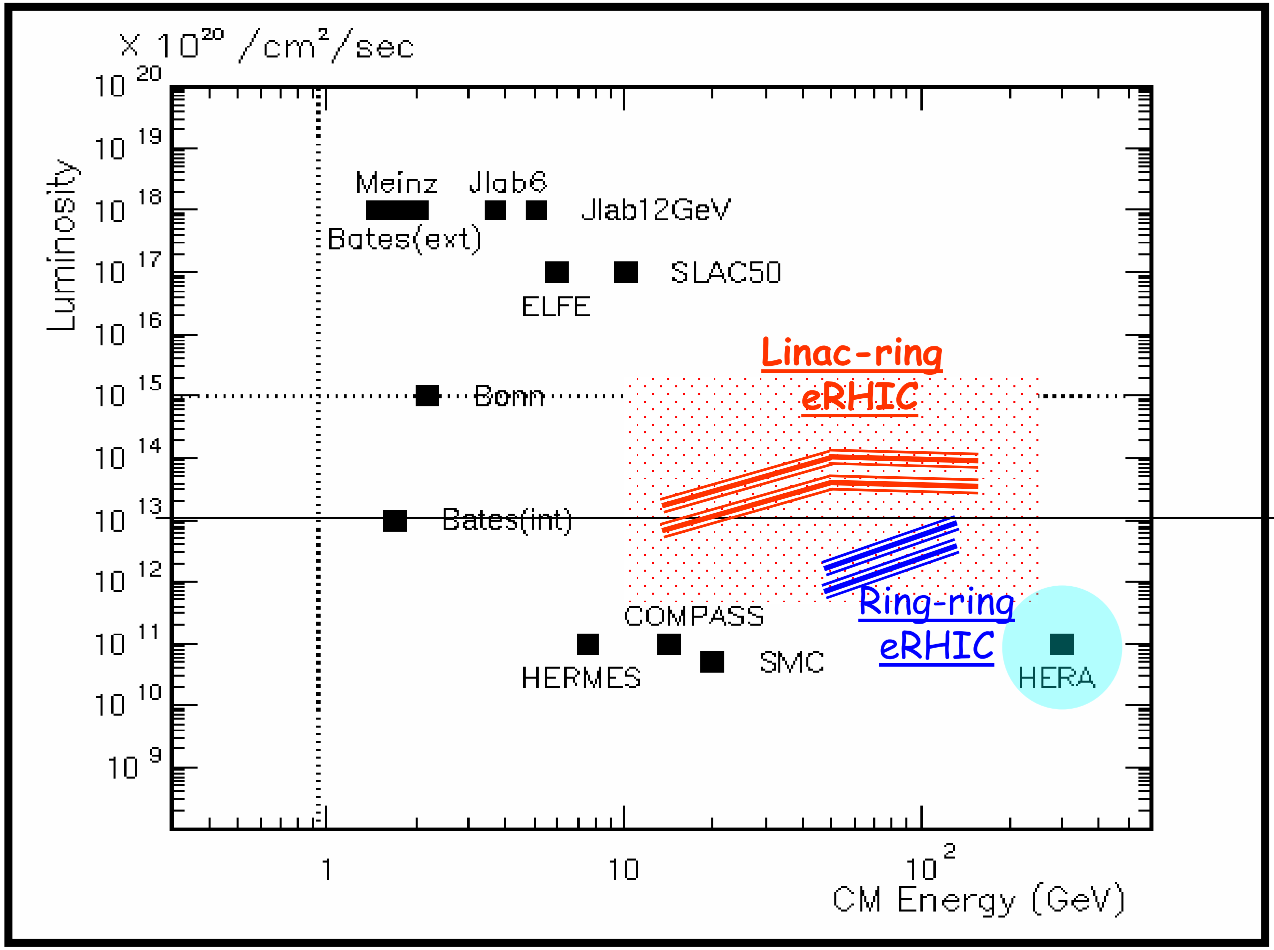


  - Linac-ring:

Electron linear accelerator



CM vs. Luminosity



eRHIC

- Variable beam energy
- Polarizes electrons and protons
- p-He^3-U ion beams
- Light ion polarization
- Large luminosity

Advantages & Disadvantages

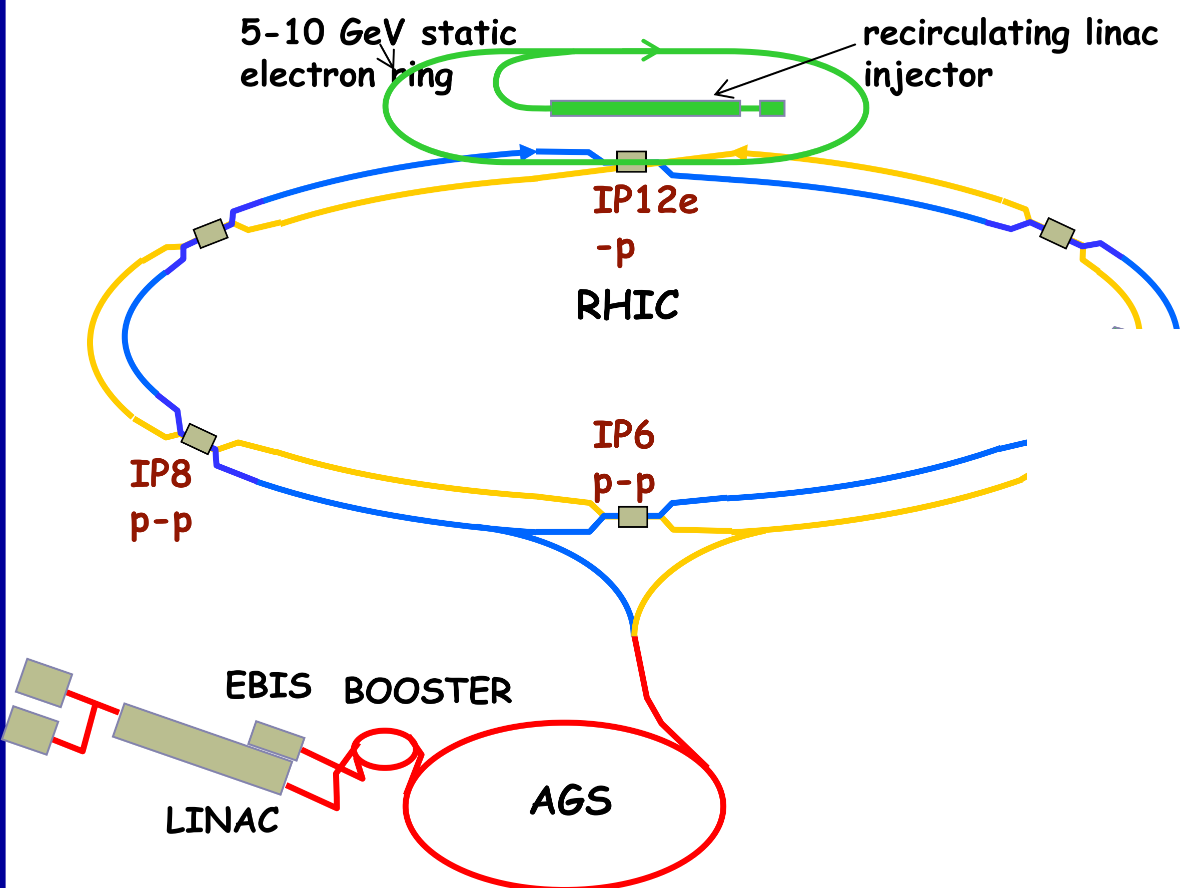
Ring-Ring

- Proven technology (B-factory)
- Supports both electron and positron (!) beams options
- Requires significant (3-fold) increase to reach $L=0.8\times10^{33}$ cm^{-2} sec^{-1} but with very short (±1 m) detector
- Reasonable detector length (±3 m) reduces luminosity for present proton/ion intensities in RHIC below or about 10^{32} cm^{-2} sec^{-1}
- Polarization is not available in forbidden energy zones
- Single IP (period).
- Machine element inside detector
- Luminosity plummets at lower E_{cm}

Linac-Ring

- High luminosity up to 10^{34} cm^{-2} sec^{-1}
- Satisfy eRHIC physics goal with present proton/ion intensities in RHIC ($L>10^{33}$ cm^{-2} sec^{-1})
- Allows multiple IPs
- No machine elements inside detector(s)
- No significant limitation on the lengths of detectors
- Allows wider range of CM-energies with high luminosities
- Full spin transparency at all energies
- Energy of ERL is simply upgradeable
- Novel technology
- Need R&D on polarized gun
- Needs a dedicated ring positrons (if required)

Ring-ring design option



- The electron ring of 1/3 of the RHIC ion ring circumference
- Full energy injection using polarized electron source and 10 GeV energy linac.
- e-ion collisions in one interaction point.
  (Parallel mode : Ion-ion collisions in IP6 and IP8 at the same time are possible.)
- Longitudinal polarization produced by local spin rotators in interaction regions.
- ZDR design luminosities (for high energy setup):
  - e-p: 4.4 10^{32} $cm^{-2}s^{-1}$
  - e-Au: 4.4 10^{30} $cm^{-2}s^{-1}$
  - e-He^3: 3.1 10^{32} $cm^{-2}s^{-1}$

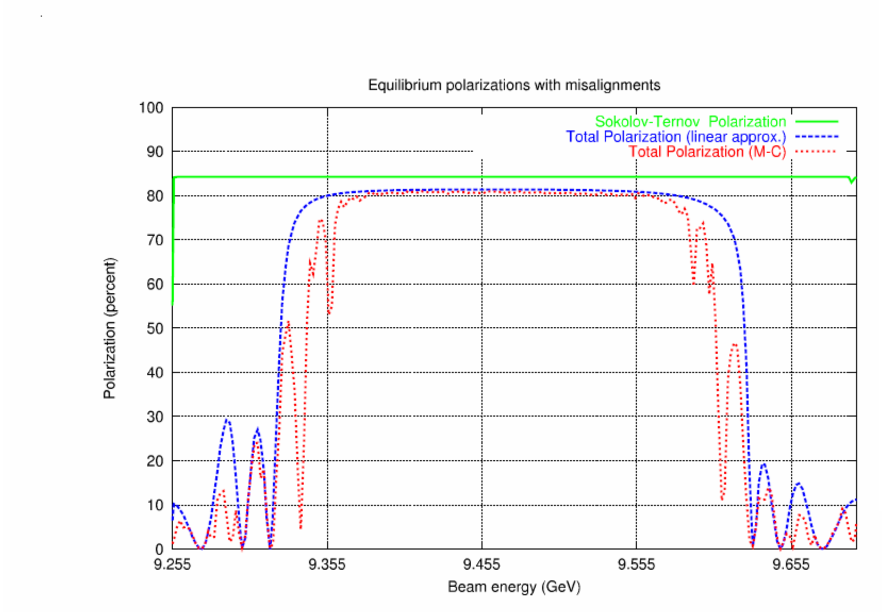
The e-ring design development led by MIT-Bates.
Technology similar to used at B-factories.

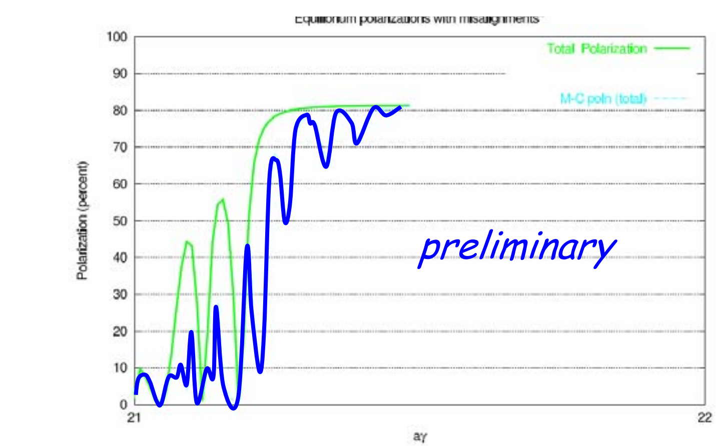
Ring-Ring developments and R&D:

- electron ring based on B-factory (MIT)
  - little R&D needed
- RHIC requires SIGNIFICANT (3X) increase in the beam intensity
  - issues of electron cloud
  - parasitic crossings

Ring-Ring: Electron polarization

Full 3–D spin motion

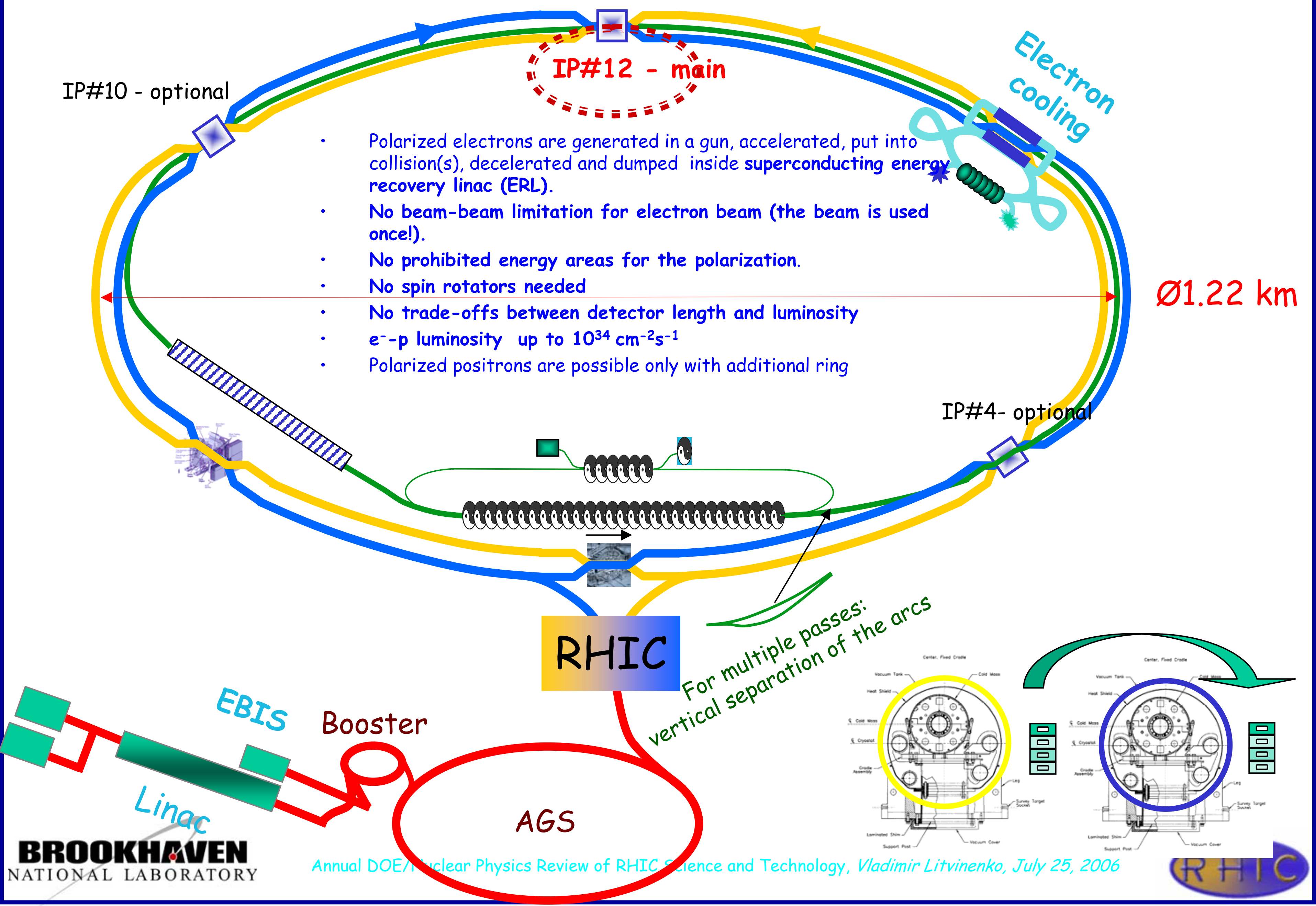




- First results for high order calculation of electron polarization indicate wide enough energy range without strong depolarization resonances.
- Open issues:
  - Compensation of depolarization from detector solenoid
  - **Possible depolarization from beam-beam effects (HERA observed polarization reduction down to 35-40%)**

D.Barber, DESY

Linac-Ring Design based on 5-20+ GeV ERL



- Polarized electrons are generated in a gun, accelerated, put into collision(s), decelerated and dumped inside **superconducting energy recovery linac (ERL).**
- **No beam-beam limitation for electron beam (the beam is used once!).**
- **No prohibited energy areas for the polarization.**
- **No spin rotators needed**
- **No trade-offs between detector length and luminosity**
- **e^--p luminosity up to 10^{34} cm^{-2}s^{-1}**
- Polarized positrons are possible only with additional ring

ERL spin transparency at all energies

Bargman, Mitchel,Telegdi equation

$$\frac{d\hat{s}}{dt}=\frac{e}{mc}\hat{s}\times\left[\left(\frac{g}{2}-1+\frac{1}{\gamma}\right)\vec{B}-\frac{\gamma}{\gamma+1}\left(\frac{g}{2}-1\right)\vec{\beta}\left(\vec{\beta}\cdot\vec{B}\right)-\left(\frac{g}{2}-\frac{\gamma}{\gamma+1}\right)\left[\vec{\beta}\times\vec{E}\right]\right]$$

$$a=g/2-1=1.1596521884\cdot 10^{-3}$$

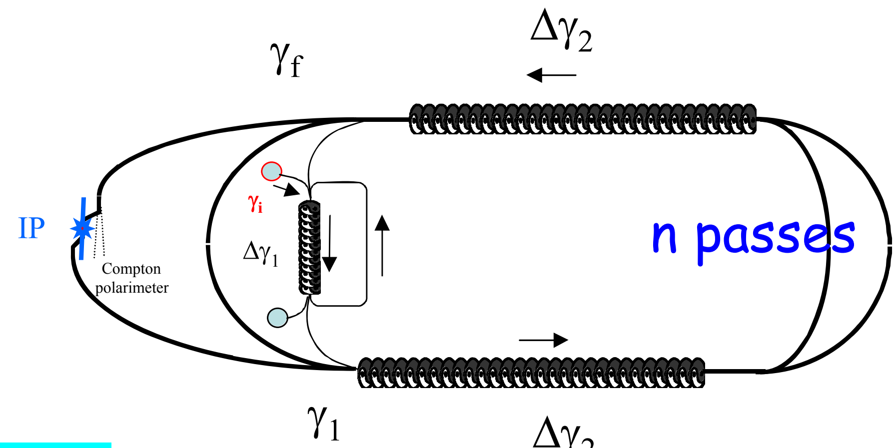
$$\hat{\mu}=\frac{g}{2}\frac{e}{m_o}\hat{s}=(1+a)\frac{e}{m_o}\hat{s};\qquad \nu_{spin}=a\cdot\gamma=\frac{E_e}{0.44065[GeV]}$$

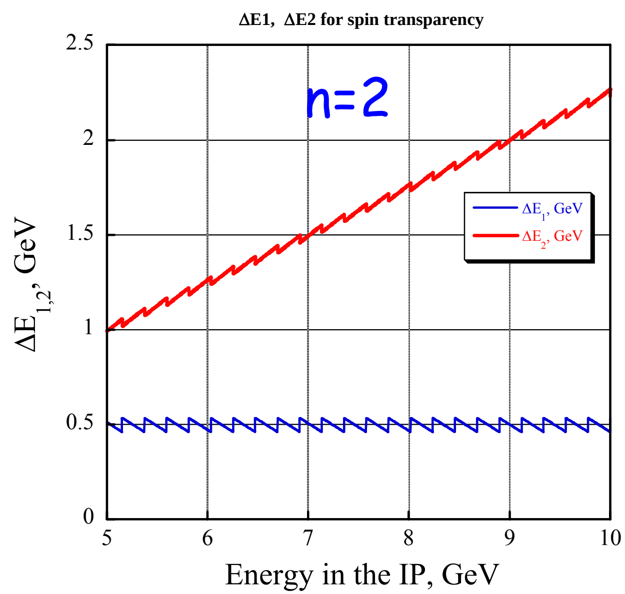
$$\Delta\varphi=a\cdot\gamma\theta$$

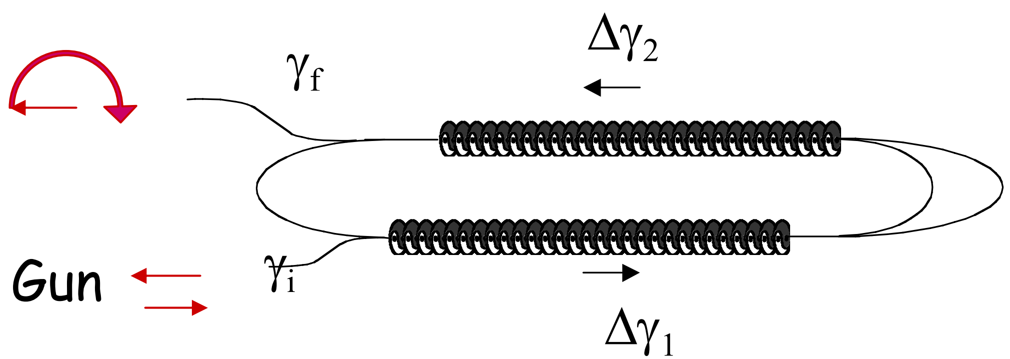
Total angle $\varphi=\pi a\cdot\left(\gamma_i(2n-1)+n(\Delta\gamma_1\cdot n+\Delta\gamma_2(n-1)\right)$

Has solution for all energies!

$$\begin{cases}\gamma_i+2\cdot(\Delta\gamma_1+\Delta\gamma_2)=\gamma_f\\ a\cdot\left(\gamma_i(2n-1)+n(\Delta\gamma_1\cdot n+\Delta\gamma_2(n-1)\right)=N\end{cases}$$

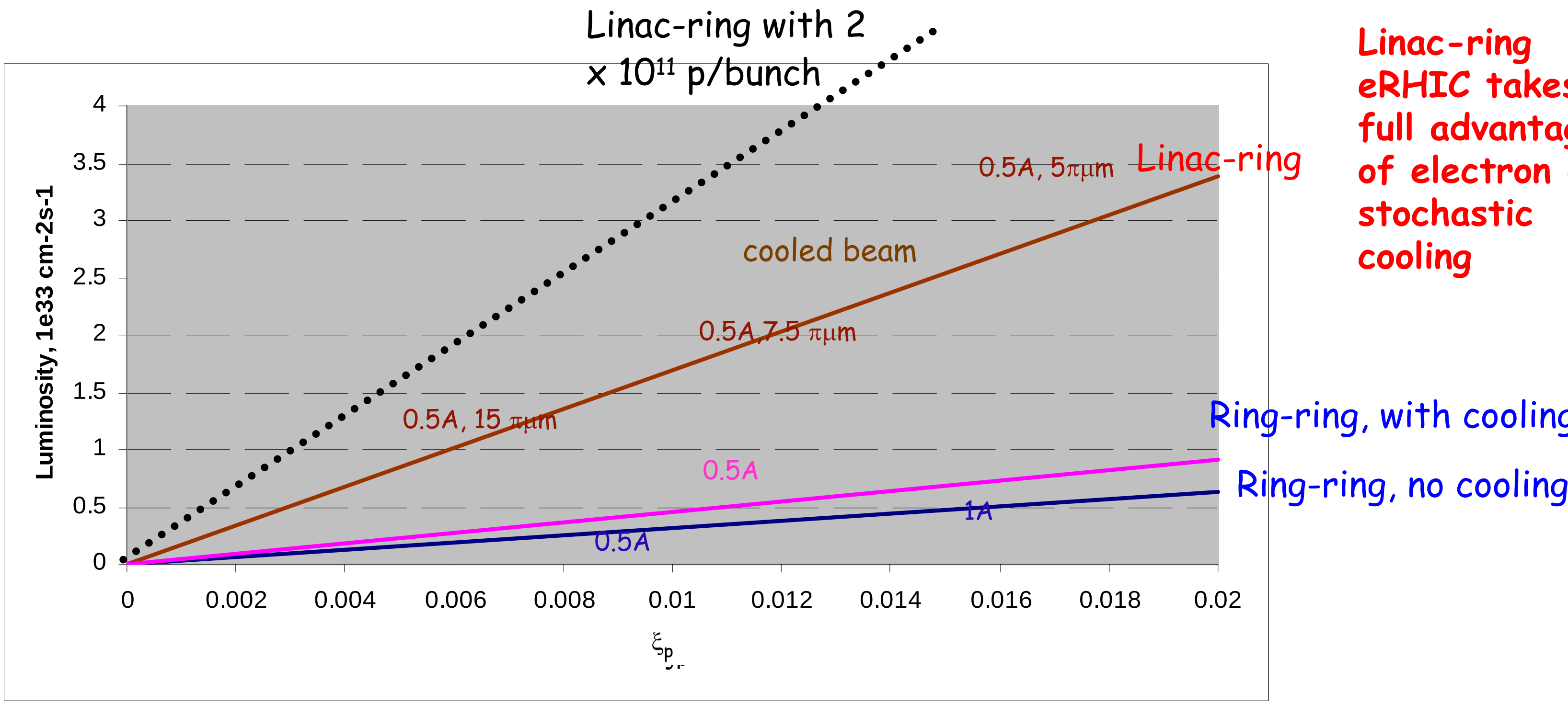






Luminosity with e-cooling

Calculations for **360 bunch** mode and 250 Gev(p) x 10 Gev(e) setup; 10^{11} p/bunch



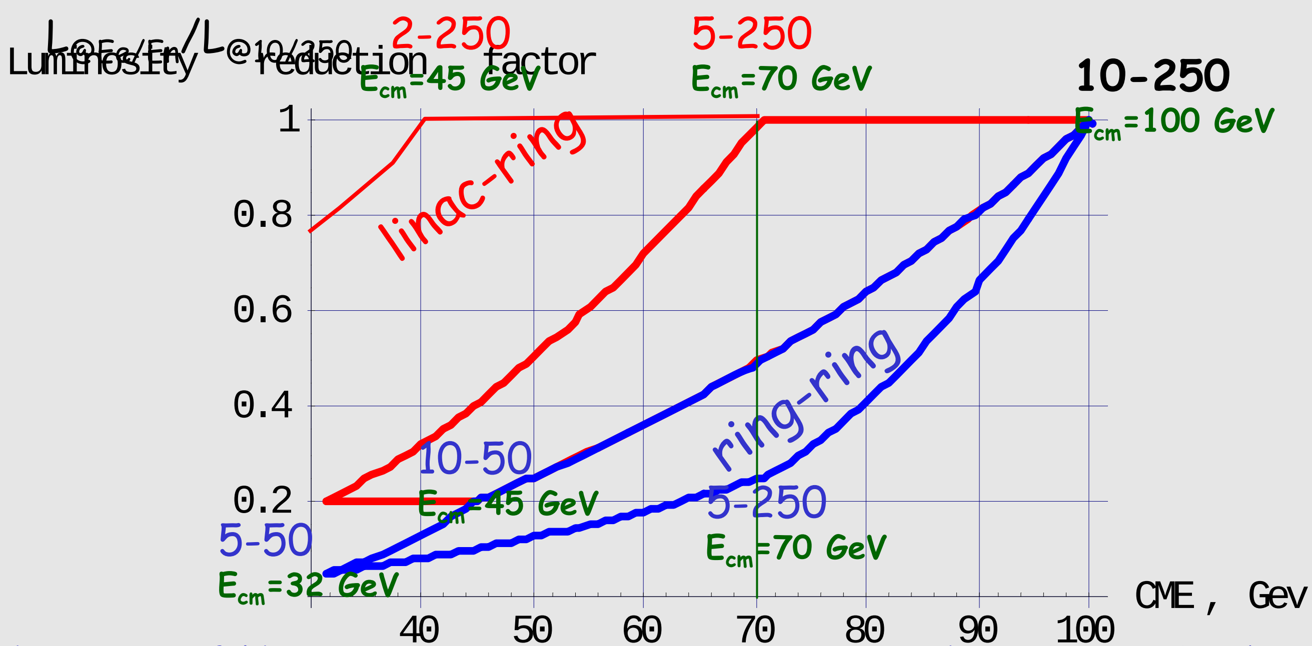
Linac-ring eRHIC takes full advantage of electron and stochastic cooling

Markers show electron current and (for linac-ring) normalized proton emittance.
In dedicated mode (only e-p collision): maximum ξ_p~0.018;

Transverse cooling can be used to improve luminosity or to ease requirements on electron source current in linac-ring option.

V. Ptitsyn

Luminosity dependence on CME with cooling

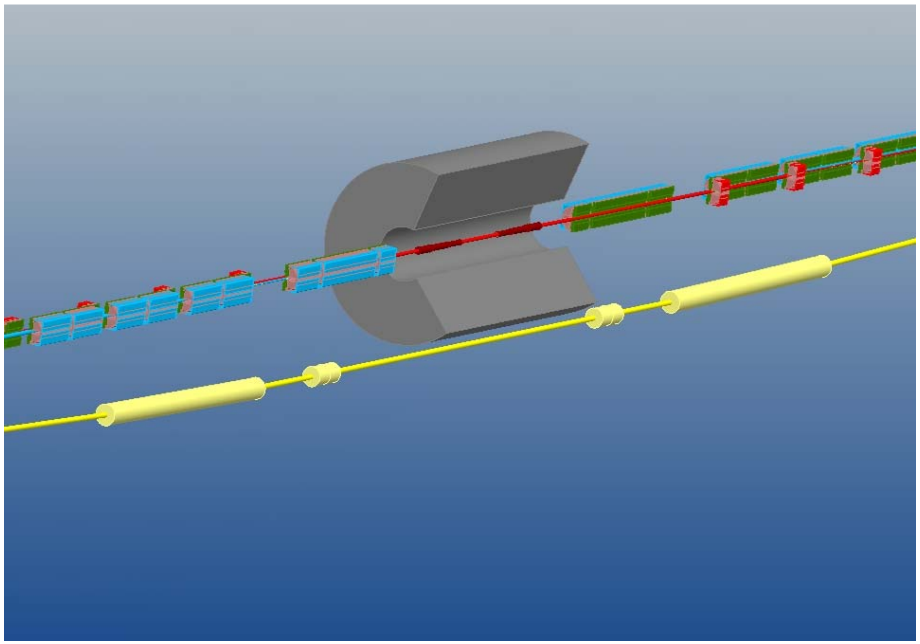


Luminosity reduction is 20-fold in ring-ring at 5GeV-50GeV set-up compared to 10GeV-250GeV (E_{cm} 100 GeV -> 32 GeV).
Required norm.emittance ~3π mm*mrad

- For ring-ring the cooling improves luminosities for low energy proton modes. The optimal curve is: 10-250-> 10-50 -> 5-50
- For linac-ring operation absence of tune shift limit on electron beam allows to maintain luminosity by keeping energy of hadron beam and reducing energy of electron beam
- Linac-ring takes full advantage of the cooling (which also reduces requirements on electron beam current).
- The optimal curve is for linac-ring : 10-250-> 5-250 -> 2-250->2-X

V. Ptitsyn

Interaction region design: affect luminosity in Ring-Ring



C.Montag, B.Parker, S.Tepikian, T.Zwart, D.Wang

- Design incorporates both warm and cold magnets.
- Provides fast beam separation. No parasitic collisions.
- Yellow ion ring makes 3m vertical excursion.
- Accommodates spin rotators (for ring-ring only) and electron polarimeter.
- Put a limit on horizontal b* for protons, because of aperture limitation in septum magnet, thus affecting achievable luminosity.
- Background produced by synchrotron radiation hitting septum magnet should not be problem (with HERA-like absorber used)

IR design schemes

	L*= Distance to nearest magnet from IP	Beam separation	Magnets used	Hor/Ver beam size ratio
Ring-ring, L*=1m	1m	Combined field quadrupoles	Warm and cold	0.5
Ring-ring, L*=3m	3m	Detector integrated dipole	Warm and cold	0.5
Linac-ring	**5m**	Detector integrated dipole	Warm	1

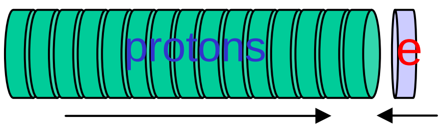
- L*= 3m is preferable for ring-ring, compared to L*= 1m, due to larger detector acceptance. The cost of the factor 2 luminosity reduction.
- Detector integrated dipole: dipole field superimposed on detector solenoid.

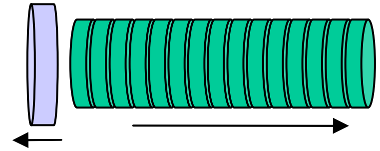
Present RHIC parameters: e-p luminosity for 112 bunches and 15$\pi\mu$m p-beam emittance 10Gev-250Gev mode

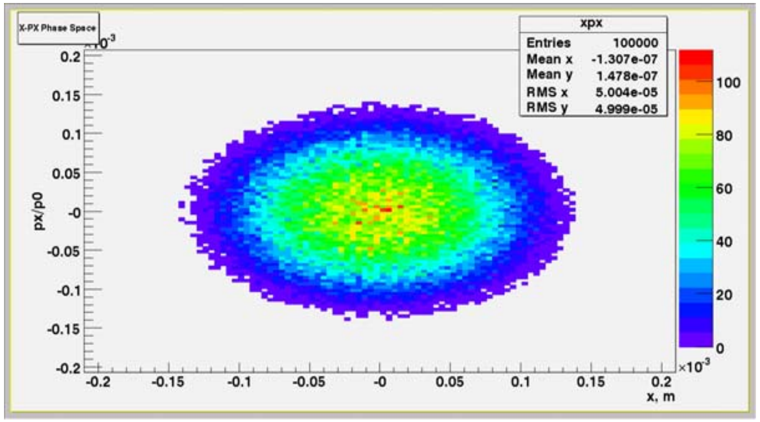
	ξ_p	Ne per bunch, 10^{11}	Total electron current, A	Luminosity, 1e33
Linac-ring	0.0049	1	0.150	0.41
	0.012	2.46	0.37	1.01
Ring-ring L*=3m design	0.0065	1	0.150	0.07
	0.013	2	0.300	0.14

V. Ptitsyn

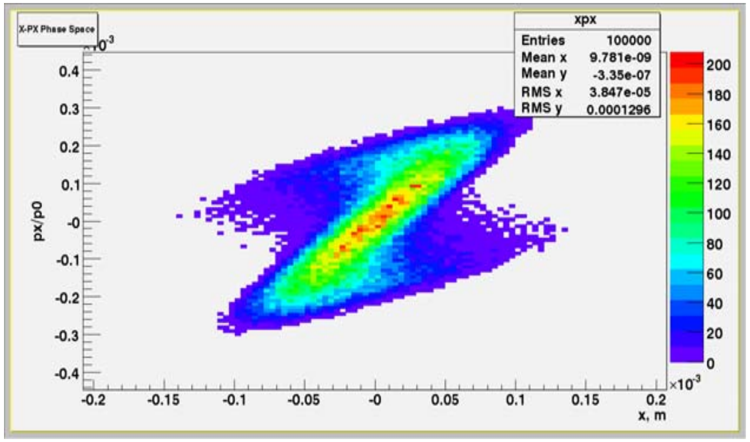
Beam Disruption -LINAC-RING (Y. Hao)



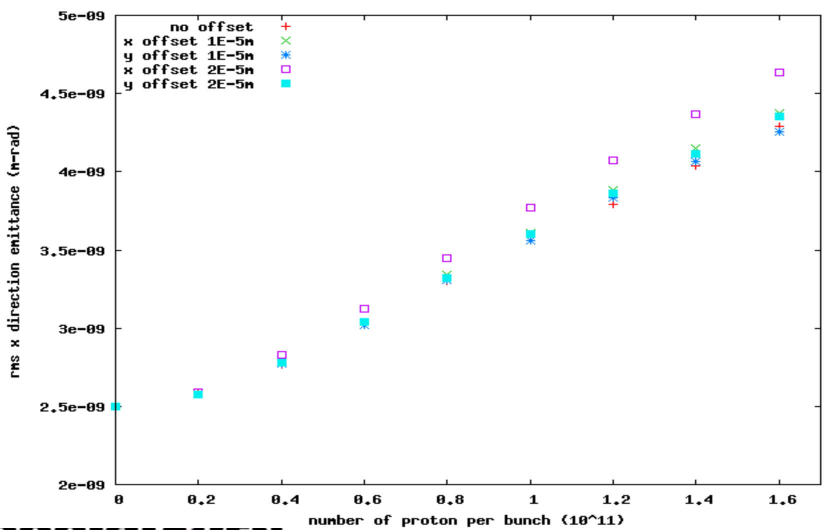


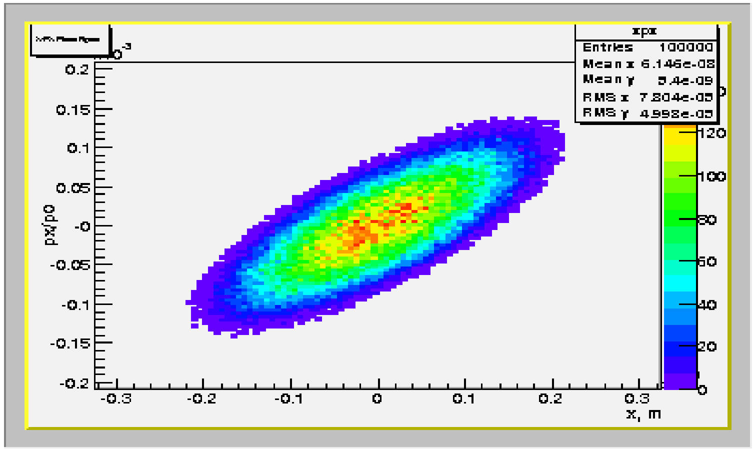


Interaction

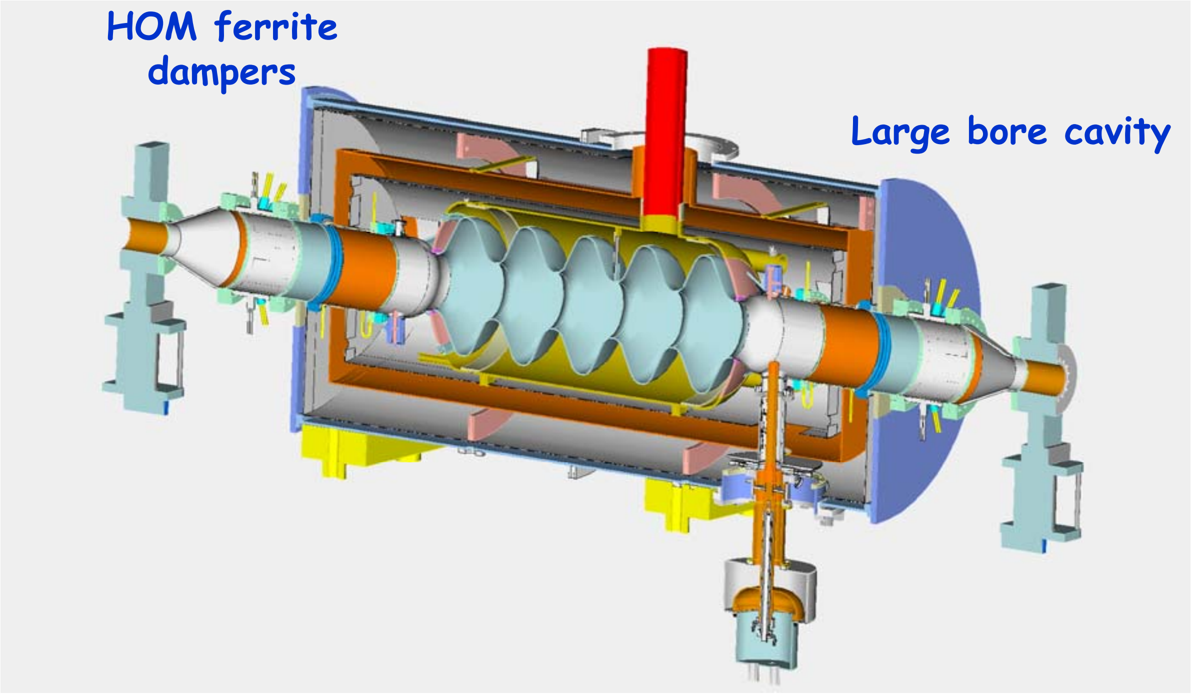


Free pass





Superconducting RF Cavity

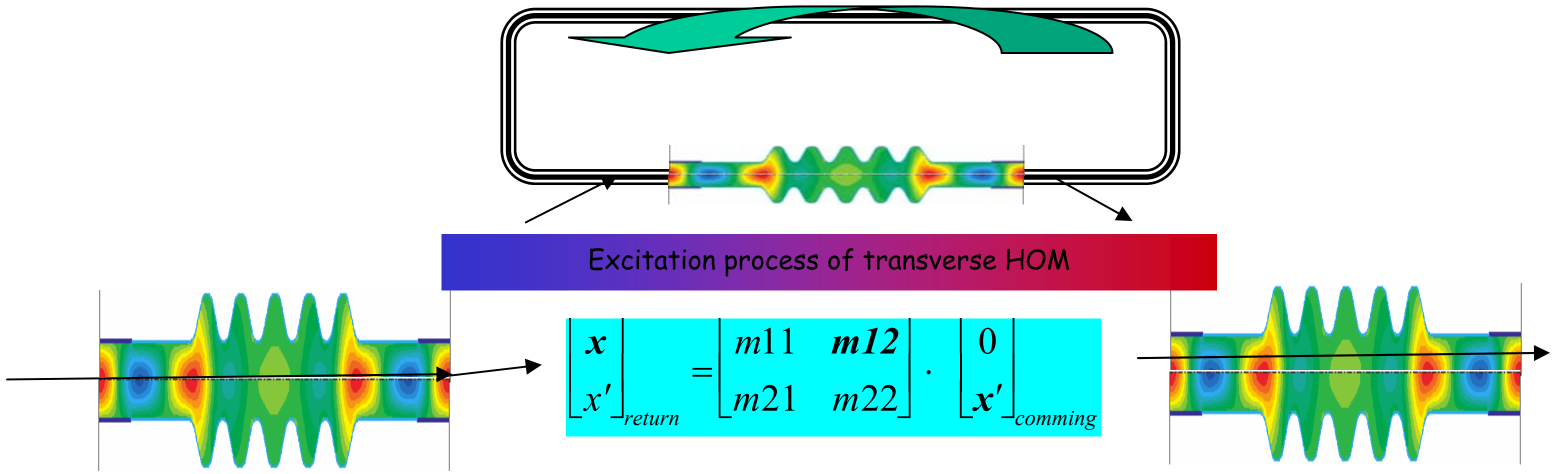


703.75 MHz 5-cell cavity designed in BNL for e-cooling and eRHIC

Cryostat assembly and cold testing in Sept.2006

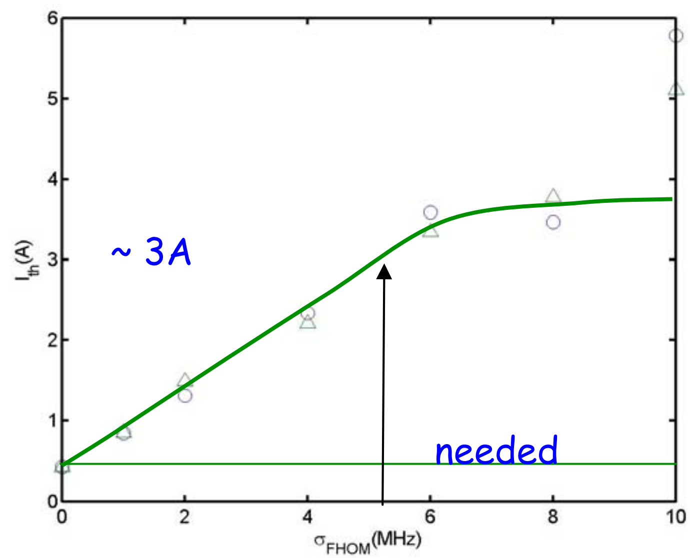
State-of-the-art cavity engineering design to minimize and damp High Order modes of electromagnetic field.

TBBU stability (E. Pozdeyev)



$$\begin{bmatrix} \boldsymbol{x} \\ x' \end{bmatrix}_{return} = \begin{bmatrix} m11 & \boldsymbol{m12} \\ m21 & m22 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ \boldsymbol{x'} \end{bmatrix}_{comming}$$

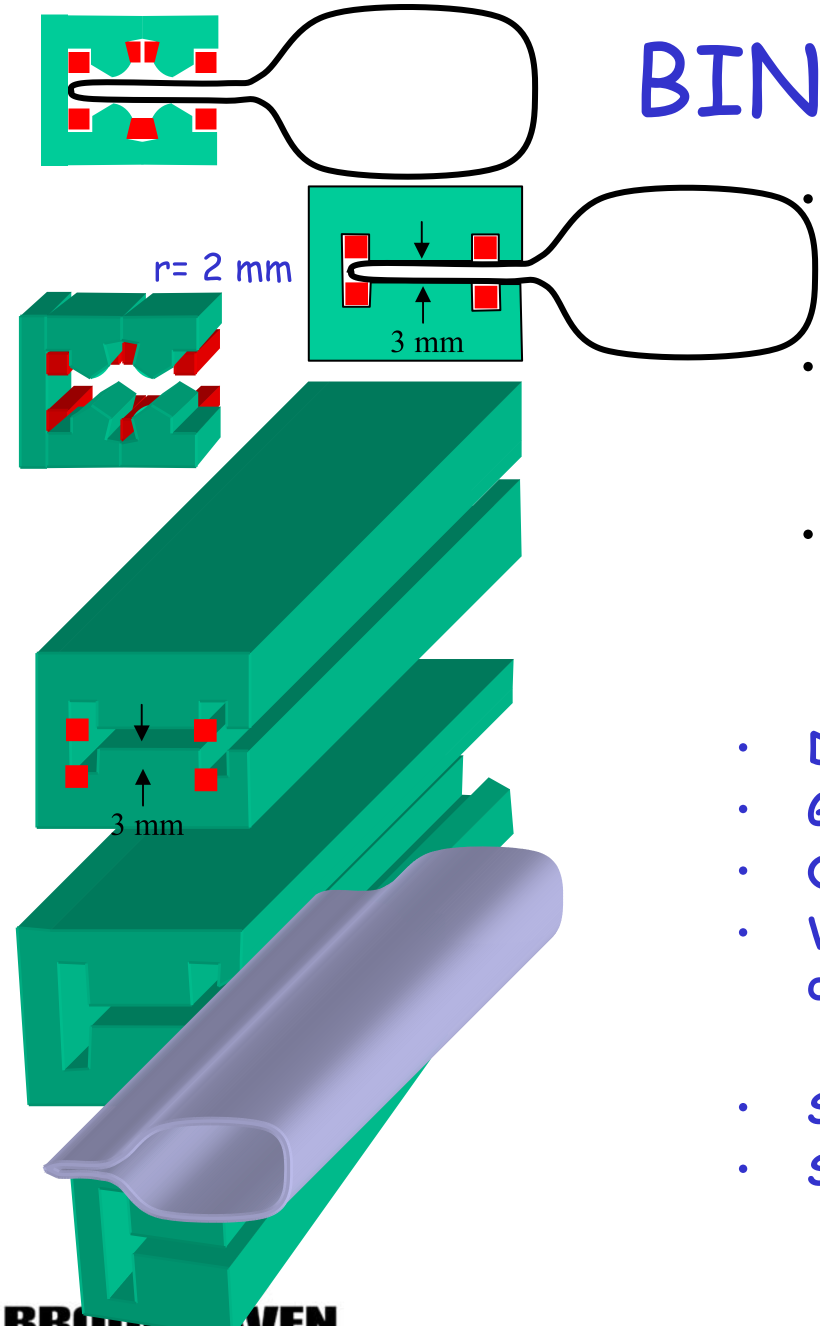
- eRHIC Linac Parameters (preliminary):
  - 200x16MeV/pass cavities (3.2 GeV gain), measured Cu-model HOM spectrum
  - 50 focusing and 50 defocusing quadrupoles, $G=\pm 1.262$ T/m
  - 3 loops around RHIC
  - 28 MHz bunch rep.rate



ERL for eRHIC: What should be aperture in magnets?

- At energy ~ 5 GeV (γ~10,000) normalized emittance ~ 10 μm rad gives emittance ~ 1 nm
- For β_{max} ~ 40 m maximum RMS size ~ 0.2 mm
- Beams from photo-guns do not have exponential tails, hence only < 1 ppm halo outside of 2-3 RMS sizes
- It means that aperture of ±1mm is sufficient
- It means that dipole gap ~ 3m is possible
- Bend radius is ~ 240 m -> dipole field 1.4 kGs
- Current per coil - 165 A
- Inexpensive, low power consumption….

BINP quote & comments



- The RHIC circumference is 3.8 km, and we plan to ~ 80% of its circumference for the returning loops
- C-type dipoled with 1.5 kGs field and ~ 3mm gap (beam stay clear ±1 mm), length from 0.5m to 10 m a piece
- 600 C-shape quads with pole-tip radius 2 mm, length 0.5 m and gradient ~ 6 kGs/cm

- **Dipoles ($900/m!) -> $2.52M per 2.8 km (loop)**
- **Girder ($450/m) -> $1.44M per loop**
- **Quads - $4500*600 -> $2.7M**
- **Vacuum chamber - $5M to $10M per loop depending on diagnostics**

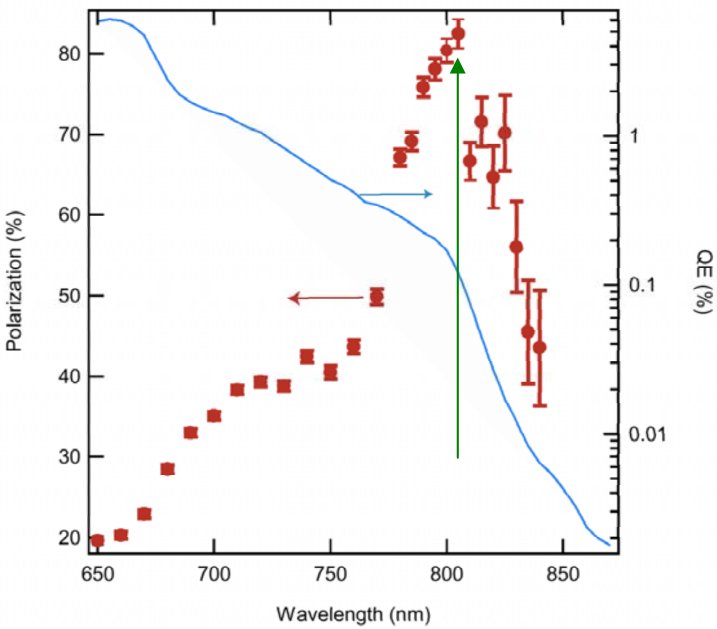
- **Suggest to increase gap to ~ 6 mm**
- **Suggest small R&D project for small gap magnets**

R&D items

- Ring-ring:
  - The accommodation of synchrotron radiation power load on vacuum chamber. (to go beyond 5.e32 $cm^{-2}s^{-1}$ luminosity).
  - Increasing total current in RHIC (ions per bunch and 3X number of bunches)
- Linac-ring:
  - High current polarized electron source
  - Energy recovery technology for high energy and high current beams
- Both eRHICs:
  - Beam cooling techniques development (electron, stochastic) in RHIC
  - Polarized He^3 production (EBIS) and acceleration

Polarized electron gun: main R&D item for MIT

Photoemission from strained GaAs cathode



- The Ring-Ring option needs a modest laser power
- For the Linac-ring use an FEL for generating high laser power with optimal pulse structure and wavelength is a good choice - needs R&D
- Scale the area of the cathode to maintain the current density
- ILC and eRHIC (linac-ring) requirements are similar:
  - Charge 2.6-3.2 (16) nC
  - Spacing 2.8-337 (36) nsec
  - Train -0.95 (CW) msec
  - Polarization >80%

Summary

- Two excellent design options for eRHIC are under development:

  Ring-Ring and Linac-Ring

- **Linac-Ring** design is based on novel accelerator technologies but has broader reach (E_{cm}) and significantly higher luminosity (~10x that of the ring-ring, i.e. **L ~ 10^{34}** $cm^{-2}s^{-1}$) for electron-hadron collisions.
  - Needs significant R&D
  - Lacks natural ability to provide polarized positions in ERL mode - I.e. will need a dedicated positron ring for such option
- **Ring-Ring** design is proven accelerator technology (but on the cutting edge)
  - The e-p luminosity of 10^{33} $cm^{-2}s^{-1}$ is **hard to achieve**
  - Luminosity strongly reduces even further
    - if detector length exceed length of 2 m
    - for lower E_{cm} energies
    - potential of de-polarization caused by collisions (like in HERA e-ring)
  - Electron and position beam polarization has "dead energy zones"

Back-up slides

Center-of-mass energies for eRHIC

Energy, GeV **protons** / **electrons** c.m.	**26**	**50**	**100**	**250**
1	10.20	14.14	20.00	31.62
2	**14.42**	20.00	28.28	44.72
5	22.80	31.62	44.72	70.71
10	32.25	44.72	63.25	**100.00**
20	45.61	63.25	89.44	141.42
30	*55.86*	*77.46*	*109.54*	*173.21*

Energy, GeV **Au/u** / **e** c.m.	**50**	**100**
1	14.14	**20.00**
2	**20.00**	28.28
5	31.62	44.72
10	44.72	**63.25**
20	63.25	89.44
30	*77.46*	*109.54*

ring-ring

linac-ring

In linac-ring eRHIC luminosity is determined by the hadron beam!

$$L = f_c \frac{N_e N_h}{4\pi\beta_h^*\varepsilon_h}$$

Round beams $\beta_e^*\varepsilon_e = \beta_h^*\varepsilon_h$

$$L = \gamma_h \cdot (f_c \cdot N_h) \cdot \frac{\xi_h \cdot Z_h}{\beta_h^* \cdot r_h}$$

In parallel with STAR and PHENIX

$$\xi_h = \frac{N_e}{\gamma_h} \frac{r_h}{4\pi Z \varepsilon_h} = 0.007$$

Luminosity 10^{33} cm^{-2}sec^{-1}	*Protons 26 GeV*	*Protons 50 GeV*	*Protons 100 GeV*	*Protons 250 GeV*
Electrons 5(2)-10(20) GeV	**0.28**	**0.52**	**0.96**	**2.8**

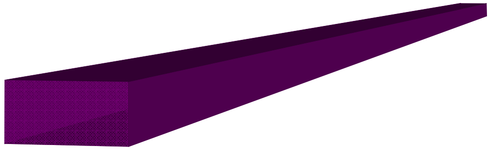
Luminosity (per nucleus) 10^{31} cm^{-2}sec^{-1}	*Au 50 GeV/u*	*Au 100 GeV/u*
Electrons 5(2)-10(20) GeV	**1.4**	**2.8**

Dedicated eRHIC mode with 250 GeV p or 100 GeV/u Au

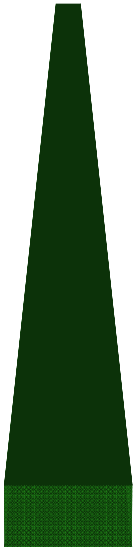
$$\xi_h \to 0.02 \quad \Leftrightarrow \quad L_{p\ e} \to 1 \cdot 10^{34}$$

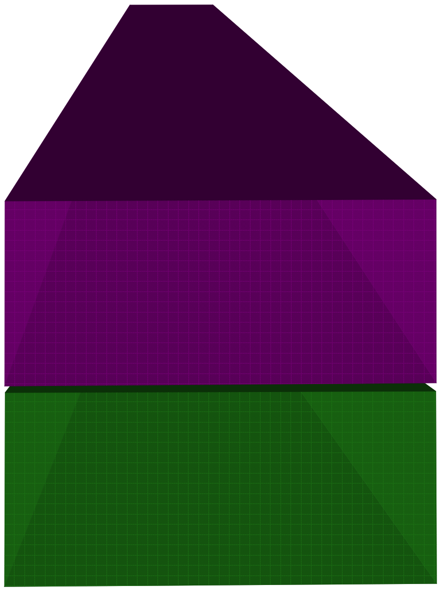
Beam parameters for linac-ring

RHIC	main case	*Present*
Ring circumference [m]	3834	
Number of bunches	360	
Beam rep-rate [MHz]	28.15	
Protons: number of bunches	360	*112*
Beam energy [GeV]	26 - 250	
Protons per bunch (max)	2.0 ¿ 10^{11}	
Normalized 96% emittance [µm]	14.5	
β^* [m]	0.26	
RMS Bunch length [m]	0.2	
Beam-beam tune shift in eRHIC	0.005	
Synchrotron tune, Qs	0.0028	
Gold ions: number of bunches	360	
Beam energy [GeV/u]	50 - 100	
Ions per bunch (max)	2.0 ¿ 10^9	
Normalized 96% emittance [µm]	6	
β^* [m]	0.25	
RMS Bunch length [m]	0.2	
Beam-beam tune shift	0.005	
Synchrotron tune, Qs	0.0026	
Electrons:		
Beam rep-rate [MHz]	28.15	*9.38*
Beam energy [GeV]	2 - 10	
RMS normalized emittance [µm]	5- 50 *for $N_e = 10^{10} / 10^{11}$ e^- per bunch*	
β^*	~ 1m, *to fit beam-size of hadron beam*	
RMS Bunch length [m]	0.01	
Electrons per bunch	0.1 - 1.0 ¿ 10^{11}	
Charge per bunch [nC]	1.6 Š 16	
Average e-beam current [A]	0.045 Š 0.45	*0.015 Š 0.15*

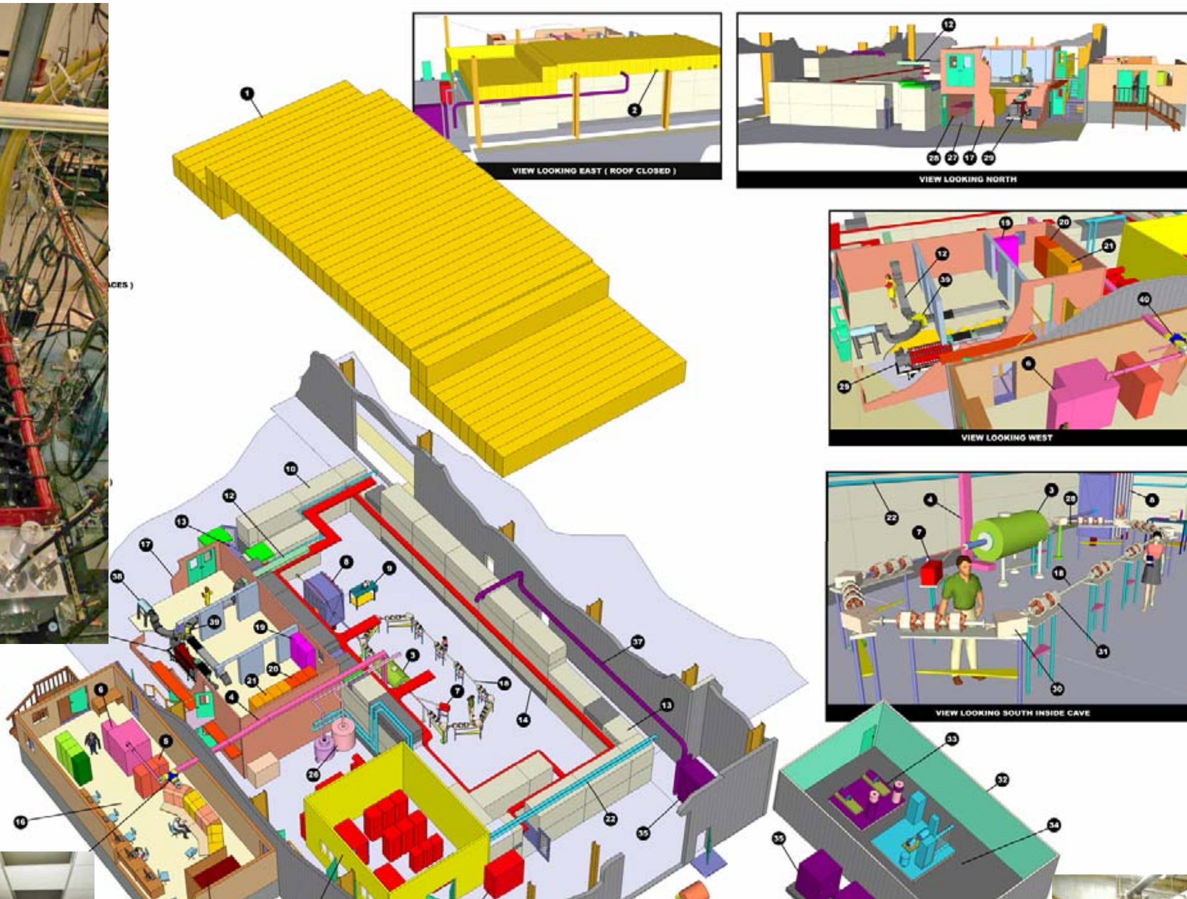


QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.





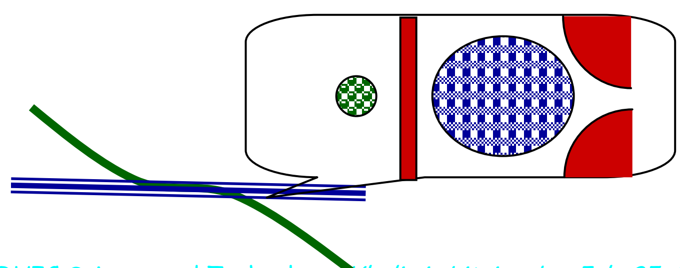
R&D ERL


VIEW LOOKING EAST (ROOF CLOSED)
VIEW LOOKING NORTH
VIEW LOOKING WEST
VIEW LOOKING SOUTH INSIDE CAVE

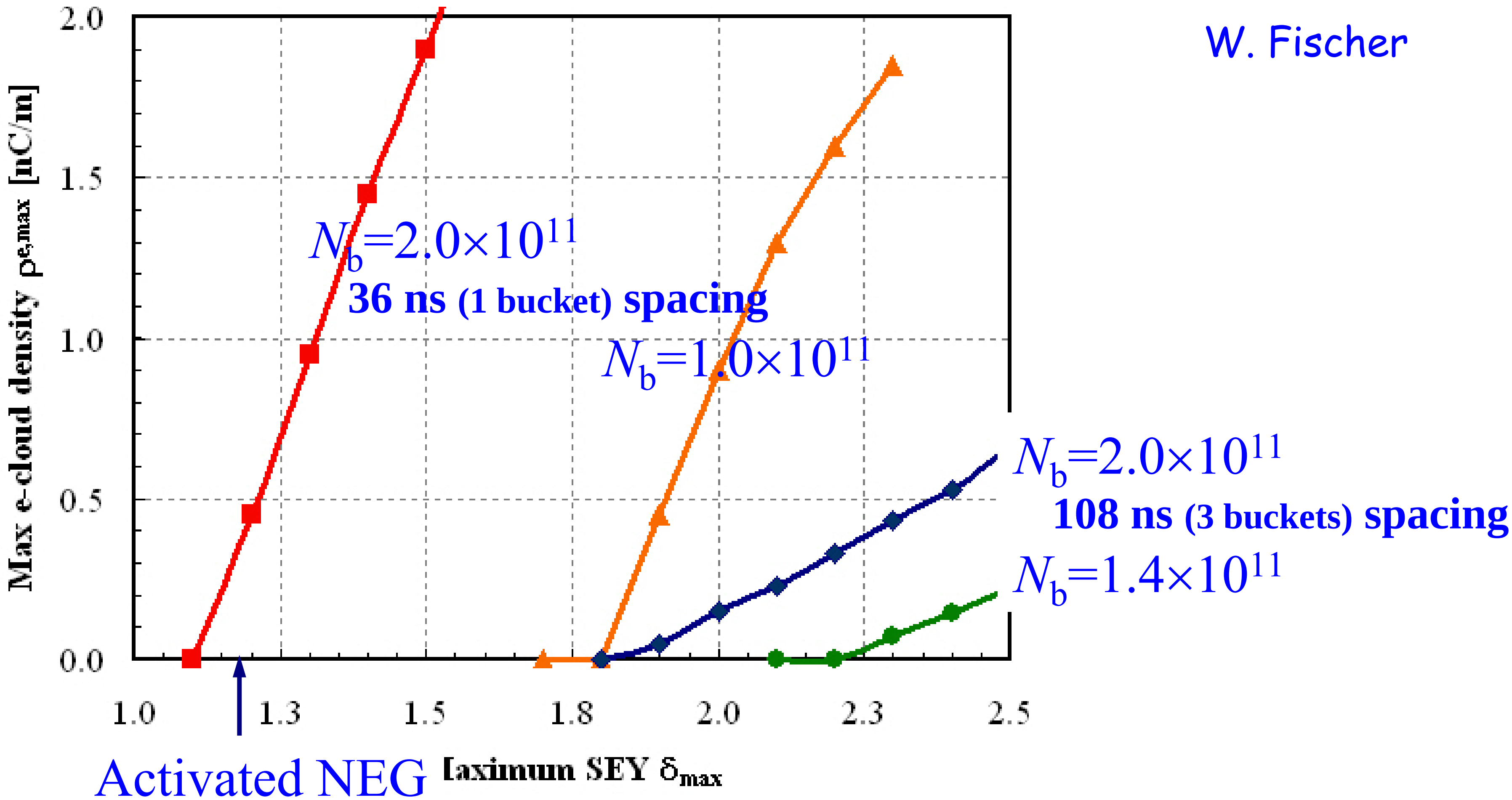
Integration with IP

$Ex = 12\sigma_{p,x} + \mathbf{5\sigma_{e,x}} + d$septum= 12¿ 0.93mm + **5 ¿ 0.25mm**+ 10mm = 22.4mm.

- Round-beam collision geometry to maximize luminosity
- Smaller e-beam emittance resulting in 10-fold smaller aperture requirements for the electron beam*
- Possibility of moving the focusing quadrupoles for the e-beam outside the detector and the IP region, while leaving the dipoles used for separating the beam
- Possibility of further reducing the background of synchrotron radiation



E-cloud in current RHIC vs. eRHIC



Expect serious e-cloud problems for N_b=2.0×10^{11} and 36 ns bunch spacing (Analysis needed for warm double beam, and cold regions also.)